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Postural sway and perceived comfort in pointing tasks

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Abstract

In this study, we explored relations between indices of postural sway and perceived comfort during pointing postures performed by standing participants. The participants stood on a force plate, grasped a pointer with the dominant (right) hand, and pointed to targets located at four positions and at two distances from the body. We quantified postural sway over 60-s intervals at each pointing posture, and found no effects of target location or distance on postural sway indices. In contrast, comfort ratings correlated significantly with indices of one of the sway components, trembling. Our observations support the hypothesis that rambling and trembling sway components involve different neurophysiological mechanisms. They also suggest that subjective perception of comfort may be more important than the actual posture for postural sway.

Keywords

End-state comfort; pointing; postural sway; rambling; trembling

1. Introduction

The mechanical design of the human body allows for multiple ways of performing typical motor tasks. Selections of specific ways from many possible constitutes resolution of the problem of motor redundancy [1]. One hypothesis about the selected solutions is that they tend to maximize subjective comfort for the aspects of the task requiring greatest control, as in ending a task when more precision is required for task completion than for task initiation [2]. Consistent with this hypothesis, when standing humans point at targets in a frontal plane, they show a reproducible pattern of comfort scores across the targets (reviewed in Rosenbaum et al. [3]). We previously hypothesized that postures perceived as uncomfortable

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would be associated with decreased stability of the hand and body. An earlier study [4] showed that comfort scores were indeed associated with overall changes in joint configuration variance though not with changes in hand stability as reflected in the structure of variance (cf. Latash et al. [5]). In the current study, we explored whether the subjective perception of comfort is associated with varying indices of postural sway across arm postures during pointing at various targets. Our main hypothesis was that postures with lower comfort scores would show higher indices of postural sway and its components.

2. Materials and methods

2.1. Subjects

Twelve young adults (6 males and 6 females, 28 ± 3 years of age, 66.1 ± 13.0 kg of mass, 1.69 ± 0.11 m of height) volunteered for the study. All participants were healthy and none reported any vision, hearing or neurological problems. None of the subjects had a recent history of injury or chronic discomfort associated with upper extremity or trunk. All participants reported that they were right–handed. Each subject signed an informed consent form according to Pennsylvania State University policy for biomedical research.

2.2. Experimental setup and procedures

During the experiment, subjects stood on a force plate (46.4 × 50.8 cm, model OR6-7-1000, Advanced Mechanical Technology, Inc., MA, USA) with eyes open or closed and feet at a self-determined comfortable width. The chosen position of the feet was marked on the force plate and was kept unchanged for all trials. A plastic hoop (diameter = 0.65 m) was placed parallel to the subject's frontal plane (Fig. 1). The hoop's center was aligned with the subject's vertical midline and adjusted to the subject's shoulder height. The hoop was placed at two relative distances from the subject: 40% and 80% of the subject's arm length. Arm length was measured from the tip of the longest finger to the anterior boundary of the armpit. During the experiment, subjects held a pointer with a power grip. The pointer was a rubber handle with a wooden rod attached to it (total length = 0.29 m, diameter of the handle = 0.03 m, total mass = 0.18 kg). Participants were asked to hold the pointer firmly, but to avoid fatigue, without excessive force.

A spherical marker, representing the target, was placed in the inner surface of the hoop at four different positions: 3, 6, 9 or 12 o'clock. The orders of target placement and relative distance were randomized between subjects. Before the experiment, participants were asked to maintain different pointing postures by first moving the right hand into the middle of the hoop and then by pointing at targets with the tip of the pointer while keeping the hand in the center of the hoop. Next, participants rated the perceived comfort of each of these postures, on a scale of 1 to 5, with 1 being "least comfortable" and 5 being "most comfortable." Participants were informed the first time they gave comfort ratings that the aim was to familiarize them with the range of comfort ratings they could use. They were encouraged to use the entire comfort-rating range and then to do the tasks one more time, assigning ratings afresh, without feeling compelled to give the same ratings again, to the extent they remembered those ratings for the individual tasks. Because it was important for participants to generate ratings afresh, and because we did not want to our participants to get fatigued,

we used just two trials per task. This general procedure for collecting comfort ratings has led to remarkably orderly data patterns in many previous studies, as reviewed by Rosenbaum et al. [3].

Trials started with participants standing up, while their arms hung naturally by their sides. On a signal from the experimenter, subjects moved the dominant hand into the middle of the hoop, pointed at the target with the tip of the pointer and maintained this pointing posture for the duration of 60 s. It was during this time that force plate data were collected. For the eyes-closed condition, subjects were asked to close their eyes after reaching the pointing posture. After 60 s, while still maintaining the pointing posture, participants were asked to open their eyes and for the second time to rate the perceived comfort of that posture. We quantified sway under the closed-eyes condition for two reasons. First, if the subjects had their eyes open, the change in the visual field by itself could affect sway. Second, standing with one's eyes closed leads to larger sway, which may be expected to have more room for comfort-related effects. During the second round of ratings, participants were told not to feel constrained to give the same ratings. Only data from this second round of ratings were analyzed. Immediately after participants rated the pointing posture, the experimenter asked them to return to the initial position. Approximately two minutes of rest were given between trials during which the experimenter changed the location of the target marker. This procedure was repeated sixteen times, once for each of the eight target locations (3, 6, 9 or 12 o'clock at 40% and 80% of arm length) in the eyes-open or eyes-closed conditions. Trials were presented in blocks such that the participant pointed to all four target-marker positions (in random order) at either 40% or 80% arm-length and then again at the other distance. Half of the participants started with the 40% distance. The other half started with the 80% distance. Subjects did not report any signs of fatigue during the experiment.

2.3. Force data analysis

The force plate coordinate system was defined with the x–axis pointing forward, along the anterior-posterior (AP) direction, the y–axis pointing to the right, along the medio-lateral (ML) direction, and the z–axis pointing downwards. The origin of the coordinate system was located at distance d_z = 4.13 cm below the top surface of the plate. Three forces (F_x, F_y, and F_z) and three moments (M_x, M_y, M_z) were collected for 60 s at 100 Hz, while participants maintained the pointing posture. The moments in counterclockwise direction were considered positive. Force plate data were low-pass filtered using a 4th-order zero-phase lag Butterworth filter with a cut-off frequency at 10 Hz. Next, the center of pressure (COP) was calculated using the following equations:

$$\mathrm{COP_{AP}}=-\frac{(\mathrm{M}_y+\mathrm{F}_x\cdot \mathrm{d_z})}{\mathrm{F_z}}\ \text{and}\ \mathrm{COP_{ML}}=\frac{(\mathrm{M_x}-\mathrm{F_y}\cdot \mathrm{d_z})}{\mathrm{F_z}},$$

where $\mathrm{COP_{AP}}$ and $\mathrm{COP_{ML}}$ are COP components along the anterior-posterior and medio-lateral directions, respectively.

The COP time series were then decomposed into the rambling (Rm) and trembling (Tr) components, using a procedure described in [6, 7]. In brief, Rm characterizes movement of

the reference point with respect to which the equilibrium is maintained, possibly reflecting supraspinal postural control. In contrast, Tr reflects deviations of the COP from the Rm trajectory due to mechanical and reflex factors. We separated Rm and Tr from the COP trajectories via several steps. First, we identified the instances when horizontal forces (F_x or F_y) were equal to zero (Fig.2, top panel). The projection of those instances onto the related COP components (COP_{AP} and COP_{ML}) represented instant equilibrium points (IEP) of the body. Next, we obtained the continuous Rm trajectories along AP and ML directions (Rm_{AP} and Rm_{ML}, respectively) by the cubic spline interpolation of the IEPs (Fig.2, middle panel). Then, we calculated the Tr trajectories along the AP and ML directions (Tr_{AP} and Tr_{ML}, respectively) as the difference between COP and Rm trajectories (Fig.2, bottom panel).

We also computed the following indices of postural sway: The area of the 95% confidence ellipse for COP displacement on the x–y plane of the force plate (areaCOP), the root–mean–square (rms) values of the COP, and the Rm, and Tr trajectories in both the AP and ML directions, referring to these as $rmsCOP_{AP}$, $rmsCOP_{ML}$, $rmsRm_{AP}$, $rmsRm_{ML}$, $rmsTr_{AP}$, and $rmsTr_{ML}$.

2.4. Statistical analysis

All descriptive statistics are reported in the text and figures as means and standard errors unless stated otherwise. To explore whether perceived comfort varied between pointing positions, we applied the Friedman nonparametric test to target positions (four levels: 3, 6, 9 or 12 o'clock) and hoop distances (two levels: 40% and 80% of the arm length). Furthermore, we applied post-hoc Wilcoxon test with Holm-Bonferroni corrections to check for differences between target positions.

We used three-way repeated measures ANOVAs to test main effects of nominal variables such as *distance* (two levels: 40% and 80% of the arm length), *target* (four levels: 3, 6, 9 or 12 o'clock), and *eyes* (two levels: opened and closed) on interval variables associated with postural sway indices: areaCOP, $rmsCOP_{AP}$, $rmsCOP_{ML}$, $rmsRm_{AP}$, $rmsRm_{ML}$, $rmsTr_{AP}$, and $rmsTr_{ML}$. To fulfill the assumption of normality, we log-transformed the dependent variables when needed. We used Greenhouse-Geisser correction when the assumption of sphericity was violated. For ANOVA results, we report p–values adjusted for multiple comparisons using Bonferroni correction.

We used correlation analysis to test the hypothesis that perceived comfort is related to postural stability. To explore relationship between ordinal and interval variables we computed polyserial correlation coefficients [4, 8] between comfort rates and postural sway indices. The relevant data were pooled from all subjects and conditions (N = 96), separately for the eyes-open and eyes-closed conditions. Because of the discrete nature of comfort ratings, some subjects used a very narrow range of comfort ratings across the pointing postures; this made computing correlations for each subject separately questionable. Hence, we decided to pool the data across all subjects. Note that we could not use correlation analysis for nominal variables, such as target distance and location, where the order of values is unknown. Significance was set at $p < 0.05$ for all statistical tests, which were performed using SPSS 19.0 (IBM Corporation, USA) and Matlab (Mathworks Inc, MA, USA) software.

3. Results

3.1. Comfort ratings of pointing postures

Comfort varied across target positions and hoop distances. The median ± interquartile range of the comfort ratings for 3, 6, 9, and 12 o'clock target directions were 3±3, 2±2, 4±2, 4.5±1, respectively, for the 40% distance and 2±1, 1.5±2, 3.5±2, 4±2 respectively, for the 80% distance. Overall, postures with the hoop placed closer to the body (40% of the arm length) and targets at the 9 and 12 o'clock positions were rated as more comfortable (with 12 o'clock target being the most comfortable). The least comfortable postures were associated with the hoop being farther away from the body (80% of the arm length) and with targets at 3 and 6 o'clock positions (with 6 o'clock target being the least comfortable). There were statistically significant differences in perceived comfort for *target* ($\chi^2(3) = 22.59$, $p < 0.001$) and *distance* ($\chi^2(1) = 4.5$, $p < 0.05$). Wilcoxon's tests confirmed significant differences between the 3 o'clock and 12 o'clock positions and also between the 6 o'clock and both 9 and 12 o'clock positions.

3.2. Effect of pointing postures on postural sway indices

Postural sway was not affected by different pointing postures. Neither target position nor hoop distance from the body affected any of the postural sway indices. Statistical analysis showed no main or interaction effects of *target* or *distance*. However, a three-way repeated measures ANOVA showed a main effect of *eyes* for most of postural sway indices. Specifically, postural sway increased when subjects performed tasks with eyes closed (areaCOP: 19.5±1.4 vs. 12.8±1.1 mm^2). All sway indices in the AP direction increased in the eyes-closed condition compared to the eyes-open condition ($rmsCOP_{AP}$: 9.6±0.5 vs 6.9±0.5 mm; $rmsRm_{AP}$: 9.3±0. 5 vs. 6.8±0.5 mm; $rmsTr_{AP}$: 1.3±0.1 vs. 0.7±0.1 mm). In the ML direction, only Tr increased in the eyes-closed condition ($rmsTr_{ML}$: 0.55±0.01 vs. 0.47±0.01 mm). These observations were statistically confirmed for areaCOP ($F_{1,11} = 48.55$, $p < 0.01$), $rmsCOP_{AP}$ ($F_{1,11} = 22.49$, $p < 0.01$), $rmsRm_{AP}$ ($F_{1,11} = 21.15$, $p < 0.01$), $rmsTr_{AP}$ ($F_{1,11} = 95.66$, $p < 0.001$), and $rmsTr_{ML}$ ($F_{1,11} = 20.29$, $p < 0.01$).

3.3. Relations between comfort ratings and postural sway indices

Among all postural sway indices, only rmsTr was reliably related to perceived comfort. In the eyes-open conditions, rmsTr in both AP and ML directions was related to perceived comfort. On average, $rmsTr_{AP}$ was 50% higher for the least comfortable postures compared to the most comfortable postures (0.9±0.05 vs. 0.6±0.06 mm for comfort ratings 1 and 5, respectively). Similarly, $rmsTr_{ML}$ for the eyes-open condition was 35% higher for the least comfortable postures when compared to the most comfortable postures (0.62±0.05 vs. 0.46±0.03 mm for comfort ratings 1 and 5, respectively).

In the eyes-closed condition, only $rmsTr_{AP}$ was related to perceived comfort. On average, $rmsTr_{AP}$ was 25% higher for the least comfortable postures compared to the most comfortable ones (1.5±0.1 vs. 1.2±0.1 mm for comfort ratings 1 and 5, respectively).

Correlation analysis confirmed these results. When participants stood with their eyes open, perceived comfort scores and rmsTr showed significant negative correlations for both AP

and ML directions ($rmsTr_{AP}$: r = –0.42, p <0.001; $rmsTr_{ML}$: r = –0.33, p < 0.001). For the eyes-closed condition, perceived comfort correlated only with rmsTr in the AP direction ($rmsTr_{AP}$: r = –0.23, p < 0.05). Table 1 contains a more detailed description of the Jaspen's correlation analysis outcomes.

Discussion

The main finding of this study was a significant correlation between rated comfort and indices of postural sway. Postural sway indices correlated with comfort scores but showed no significant dependence on target distance and location. In addition, only one component of the sway, namely trembling (Tr), showed such correlations.

From these outcomes, we conclude, first, that our main hypothesis has been confirmed: Comfort is related to stability of the body as a whole. These results stand in contrast to an earlier study that focused on the analysis of joint configuration variance across repetitive trials [4] where comfort ratings correlated with the overall magnitude of joint configuration variance while the relative amount of variance compatible with the pointer final position was unchanged. Note that the latter index has been considered an index of stabilization of the pointer location and orientation [9, 10]. The differences between the results of the two studies may originate from the fact that one of them quantified stability of the pointer, while the other explored postural sway of the whole body. Taken together, the two studies lead to a conclusion that subjective perception of comfort is related to the whole-body equilibrium (reflected in sway characteristics, namely rmsTr), not to posture of the pointing effector. These findings are consistent with a view that an action by a standing person should be considered a whole-body action, without distinct movement and postural components, even if no major whole-body deviation is seen (cf. Aruin and Latash [11]).

Rm and Tr have been considered as distinct components of postural sway potentially reflecting different neurophysiological and mechanical factors. A few studies reported different changes in Rm and Tr characteristics with changes in conditions of postural tasks [12,13]. Our results provide further support for the different origins of Rm and Tr. Indeed, only Tr characteristics correlated with subjective comfort scores. One possibility is that standing in a subjectively less comfortable posture may be associated with increased muscle co-contraction, which, by itself, does not affect the equilibrium position of the body but may change mechanical and reflex properties of muscles thus leading to changes in Tr. Note that increased muscle co-contraction has been reported for populations with increased postural sway such as older adults, patients with neurological disorders, and persons with Down syndrome (reviewed in [14], [15]). The fact that Tr characteristics changed not with posture but with subjective perception of comfort (cf. the results of Mochizuki et al. [16]) suggests that muscle co-contraction may be very sensitively picked up by actors when it is not reflected in objective differences in postural tasks.

While comfort ratings changed consistently across target location and distance, these changes might be affected by many physiological, psychological and biomechanical factors. In an earlier study [4], we have shown that comfort rating correlated with the overall variance in the joint configuration space. In this study, we show that comfort ratings co-vary

with postural sway indices, possibly related to muscle co-contraction and, consequently, to energy expenditure [17]. Note that muscle co-contraction could happen not only in leg and trunk muscles but also in the upper limb muscles for target locations perceived by the subjects as less comfortable. The general issue of the origins of different comfort ratings, however, is too broad to be addressed comprehensively in this study.

Acknowledgments

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Highlights

- We explored relations between postural sway and perceived comfort during pointing postures.
- Different pointing postures had no effect on postural sway.
- Perceived comfort correlated with one of the postural sway components, trembling.
- Postural sway is defined more by perceived comfort than by the actual posture.

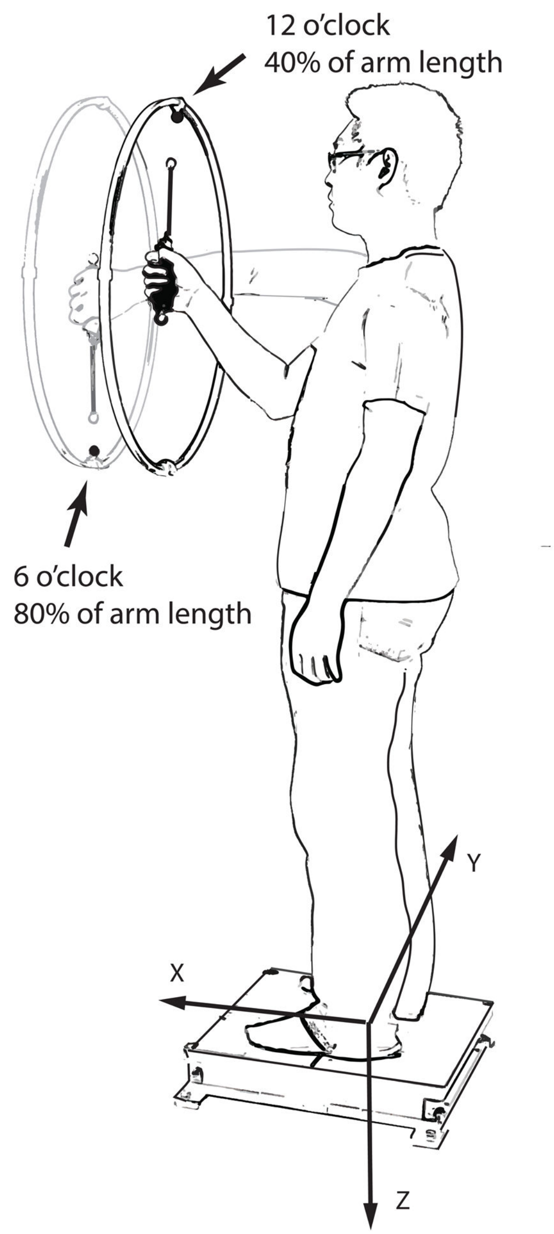

Figure 1.

The experimental setup for the pointing task. Subject stood on the force plate and maintained a pointing posture. The plastic hoop was placed at the two relative distances: 40 and 80% of the participant's arm length. A reflective target marker was placed on the inner surface of the hoop either at 3, 6, 9, and 12 o'clock positions. X, Y, and Z-axes represent force plate coordinate system. Figure shows an example of two pointing postures, with two target positions at two hoop distances.

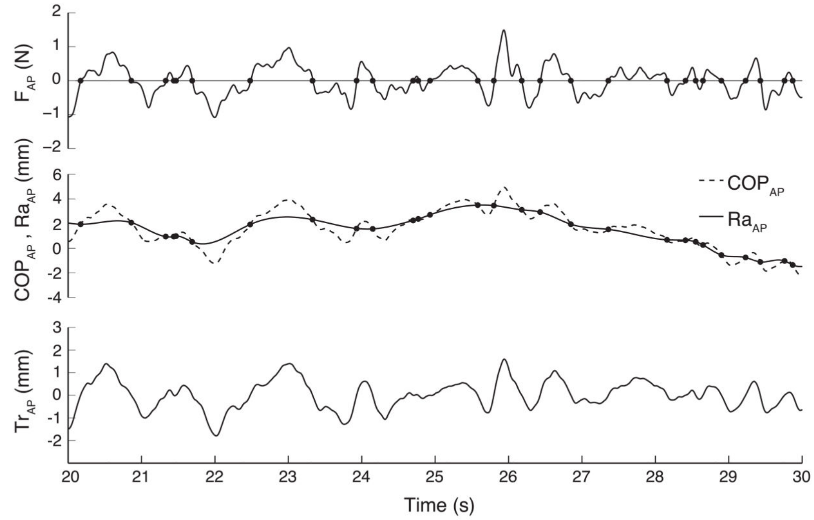

Figure 2.

An example of rambling (Rm) and trembling (Tr) decomposition from the COP trajectories. Top panel shows a horizontal force trace (F_x) with identified instances when F_x is equal to zero. Middle panel shows projection of those instances on the COP_{AP} (dashed line), which represents instant equilibrium points (IEP, black dots) of the body. Next, the continuous Rm trajectory along AP directions ($Rm_{AP)}$ is obtained by cubic spline interpolation of the IEP (solid line). The bottom panel shows the Tr trajectory along AP directions (Tr_{AP}) that was calculated as a difference between COP_{AP} and Rm_{AP} trajectories. Please note that for clarity, this example shows only a 10-s long data set from the 60-s long trial.

Table 1

Summary of the Jaspen's correlations between comfort ratings and postural sway indices.

	Eyes opened		**Eyes closed**	
Postural sway indices	***r***	***p***	***r***	***p***
areaCOP	−0.13	0.22	−0.04	0.72
$rmsCOP_{AP}$	−0.02	0.88	0.05	0.61
$rmsCOP_{ML}$	−0.14	0.18	−0.11	0.28
$rmsRm_{AP}$	−0.01	0.93	0.05	0.61
$rmsRm_{ML}$	−0.14	0.18	−0.10	0.32
$rmsTr_{AP}$	**−0.42**	**0.00**	**−0.23**	**0.03**
$rmsTr_{ML}$	**−0.33**	**0.00**	−0.20	0.06

Bold fonts indicate statistically significant correlations at $p < 0.05$